

Sharp Infrared Eyes

The Journey of QWIPs from Concept to Large Inexpensive Sensitive Arrays in Hand-held Infrared Cameras

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ABSTRACT

One of the simplest device realizations of the classic *panicle-in-a-box* problem of basic quantum mechanics is the Quantum Well Infrared Photodetector (QWIP). Optimization of the detector design and material growth and processing has culminated in the realization of a camera with a large (256x256 pixel) focal plane array of QWIPs which can see at 8.5 μm , holding forth great promise for a variety of applications in the 6-25 μm wavelength range. The world's first hand-held infrared camera at these long wavelengths, it features the Jet Propulsion Laboratory's QWIP technology and was jointly developed by JPL and Amber. This paper discusses the physics and technology of the QWIP and reports on the camera's performance.

INTRODUCTION

The human eye can see only a small slice (blue to red) of the light spectrum. Only objects that are hot enough to glow at these colors and those that reflect visible light appear visible to the eye. Most objects, however, are too cold to glow visibly, making them invisible at night. But their finite temperature does give them a infrared glow. It is this glow (or its reflection) that night-vision infrared cameras strive to see. Recent developments at the Jet Propulsion Laboratory have culminated in one of the most sensitive yet affordable hand-held long wavelength infrared (LWIR) camera.

Uses for infrared (IR) cameras range from the prosaic to the provocative. Objects at room temperature glow brightest in the wavelength range of 8-10 μm . Cameras that can see 8.5 μm light find uses in security and surveillance, navigation and flight control, early-warning systems, etc. Such a camera's ability to produce a thermal map of the surface of human skin offers applications in medical imaging. Since most of the absorption lines of gas molecules lie in the 1-10 μm spectral region, IR cameras can be used to monitor and measure pollution, relative humidity profiles, and the distribution of different gases in the atmosphere. Ground-based telescopes fitted with these cameras can stare out the 8-12 μm transparent window in the earth's atmosphere, image distant stars and galaxies (including those invisible to telescopes equipped with normal visible eyes), and help in the search for cold objects such as planets orbiting nearby stars. Defense, commerce, and science, all stand to benefit from sharper, affordable IR cameras.

At the heart of an IR camera (in its focal plane) is its eye: a 2-dimensional array of detector pixels, each pixel converting some of the photons (composing the IR light) striking it to an electric signal. The rest of the camera is optics (to zoom and focus on a scene), a cooling system (to increase the sensitivity of the eye), and electronics (to produce a standard video signal). Recent years have seen a drive to larger arrays since larger arrays offer greater image resolution.

THE QWIP

A quantum well designed thus to detect infrared light is called a Quantum Well Infrared Photodetector (QWIP). An elegant candidate for QWIP is the square quantum well of basic quantum mechanics. When the quantum well is sufficiently deep and narrow, its energy states are quantized (discrete). The potential depth and width of the well can be adjusted so that it holds only two energy states: a ground state near the well bottom, and a first excited state near the well top. A photon striking the well will excite an electron in the ground state to the first excited state, whence an externally-applied voltage sweeps it out producing a photocurrent (Fig. 1). Only photons having energies corresponding to the energy separation between the two states are absorbed, resulting in a detector with a sharp absorption spectrum. Designing a quantum well to detect light of a particular wavelength becomes a simple matter of tailoring the potential depth and width of the well to produce two states separated by the desired photon energy. The QWIP might have remained a textbook curiosity had it not been for the spectacular advances

within the last 20 years in the crystal growth and processing techniques of large bandgap compound semiconductors such as GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$.

A quantum well can be realized by sandwiching a layer of GaAs between two layers of $\text{Al}_x\text{Ga}_{1-x}\text{As}$. The well width is controlled by controlling the GaAs layer thickness; the potential depth is controlled by controlling the Al composition x in the barrier layers. Modern crystal-growth methods like molecular beam epitaxy (MBE) allow the growth of highly uniform and pure crystal layers of such semiconductors on large substrate wafers, with control of each layer thickness down to a fraction of a molecular layer. In other words, a textbook square quantum well of the desired shape can be produced. The $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ material system allows the quantum well shape to be tweaked over a range wide enough to enable light detection at wavelengths longer than $\sim 6 \mu\text{m}$. Stacking several identical quantum wells (typically 50) together increases photon absorption. Ground state electrons are provided in the detector by doping the GaAs well layers with Si. Fabricated entirely from large bandgap materials which are easy to grow and process, it is now possible to obtain large uniform FPAs of QWIPs tuned to detect light at wavelengths longer than $\sim 6 \mu\text{m}$ in the $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ material system.

DARK CURRENT

Improving QWIP performance depends largely on minimizing the parasite that plagues all light detectors: the dark current (the current that flows through a biased detector in the dark, i.e., with no photons impinging on it). The dark current in QWIPs originates from three different mechanisms (Fig. 1). Sequential tunneling of ground state electrons from well to well dominates the dark current at temperatures less than 30 K and can be reduced by widening the barriers. At intermediate temperatures, a second mechanism kicks in: thermionic emission of ground state electrons toward the well top followed by tunneling through the barrier tip into the energy continuum above the wells and barriers. At temperatures above 45 K, the dark current is entirely dominated by classic thermionic emission of ground state electrons directly out of the well into the energy continuum. Minimizing this last component is critical to the commercial success of the QWIP as it allows the highly-desirable high-temperature camera operation,

We design the *bound-to-quasibound* quantum well by placing the first excited state exactly at the well top (Fig. 2). The best previous QWIPs (pioneered by Barry Levine *et*

al. at AT&T Bell Labs) were of the bound-to-continuum variety, so-called because the first excited state was a continuum energy band above the well top (typically 10 meV). Dropping the first excited state to the well top causes the barrier to thermionic emission (roughly the energy height from the ground state to the well top) to be -6 meV more in our bound-t,o-quasibound QWIP than in the bound-to-continuum one, theoretically causing the dark current to drop by a factor of ~ 3 at a temperature of 70 K. This compares well with the factor of ~ 4 drop we experimentally observe (Fig. 2). Importantly, the bound-to-quasibound QWIP still preserves the photocurrent. One could push the first excited state deeper into the well to increase the barrier to thermionic emission even further, but this would drop the photocurrent to unacceptably low levels.

We further reduce the dark current by drastically cutting the well doping density to decrease the number of ground state electrons available for thermionic emission, and by increasing each barrier thickness in the multi-quantum-well (MQW) stack to 60 nm; any further decrease in well doping or increase in barrier thickness causes no significant enhance in signal-to-noise ratio.

With all these fine-tunings, an optimized bound-to-quasibound QWIP operating at a peak wavelength of 8.5 μm consists of a MQW stack of 50 GaAs quantum wells, each well 5 nm wide and separated from its neighbors by ~ 60 nm thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers with $x \sim 0.3$. Grown by MBE, the MQW stack is itself sandwiched between top and bottom Si-doped contact layers.

LIGHT COUPLING

A key factor in QWIP focal plane array (FPA) performance is the light coupling scheme. This is caused by a selection rule peculiar to $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ QWIPs: light striking the quantum well layers normally is *not* absorbed; to be absorbed, the light has to have a component of its electric field in the quantum well direction. Light being a transverse wave, this requires bending the normally incident light inside the detector. This is done with mirrors,

A simple scheme is to put a special mirror on the detector top and illuminate the detector from the back. A *smooth* top mirror is useless: it simply reflects the light straight back out. To be useful, the mirror has to be *rough* (on the scale of the light's wavelength in GaAs). Light normally entering through the back side and striking a rough top mirror

is scattered back in a cone, This cone now strikes the back side. Those rays that **are** within a critical angle of the normal (17° for the GaAs-air interface) escape out. The rest suffer total internal reflection with the back surface acting as a smooth mirror. The internally reflected rays are once again reflected off the top rough mirror. What happens next depends on whether the roughness of the top mirror is periodic or random. If it is periodic, the top mirror **will** bend these rays so that they are all normal to the quantum well layers again. These rays pass through the detector and out from the back side. A **randomly** roughened mirror, on the other hand, will randomly scatter all the rays internally reflected on to it from the back side **each time**, allowing the incident light to bounce back and forth between the detector top and back surfaces several times (Fig. 3). Only light within a 17° (from normal) cone escapes out from the back side. Clever design can reduce the amount of light in the escape cone but cannot eliminate it altogether. For instance, if the random reflector is designed with two levels of rough surfaces having the same areas but located a quarter wavelength apart, the **normally** reflected light intensities from the top and bottom surfaces of the reflector are equal and 180° out of phase (i.e., phase plate). This maximizes the destructive interference at normal reflection and lowers light leakage through the escape cone.

On each pass through the MQW region some of the bent light is absorbed. A periodic mirror thus offers two useful passes, a random mirror several. Trapping the most light with a rough mirror requires increasing the detector aspect ratio (diameter/height), accomplished by thinning the - $600\text{ }\mu\text{m}$ thick GaAs substrate on top of which the MQW stack is grown, to about zero. This approximate] y **doubles** the light absorbed in the periodic mirror **case**; it **quadruples** it when a **random** mirror is used.

FIGURES OF MERIT

Responsivity and defectivity are two figures of merit commonly used to compare photodetectors. Responsivity is the ratio of the photosignal to the radiation power incident on the detector. The higher the responsivity, the more sensitive the detector. Fig. 2 inset shows typical photorcsponse curves of bound-to-quasibound and **bound-to-**continuum $8.5\text{ }\mu\text{m}$ QWIPs at a temperature of 77 K. The first excited state resonating with barrier top results in sharper absorption and photoresponse for the former compared to the latter. The **responsivity** of the **bound-to-quasibound** QWIP peaks at $8.5\text{ }\mu\text{m}$ with a peak value of 300 mA/W at a bias of -3 V . The spectral width and cutoff wavelength are

10% and 8.9 pm, respectively. Its peak quantum efficiency (a measure of the number of photoelectrons generated by each photon striking the QWIP) is 6.9% at a bias of -2 V.

Detectivity (D^*) is the signal-to-noise ratio normalized to unit area and unit bandwidth. The main noise source in QWIPs is the shot noise caused by the dark current. Unlike narrow bandgap detectors in which the noise is dominated by temperature-independent processes at low temperatures, QWIP performance can be dramatically improved by cooling to cryogenic temperatures to exponentially reduce the dark current (and the shot noise it produces). The D^* value today for a 9 μm QWIP measures $\sim 10^{11} \text{ cm}^2/\text{Hz/W}$ at 70 K, and rises exponentially with cooling. Such a D^* value is more than sufficient to demonstrate large two-dimensional imaging arrays (256x256 pixels or larger) at long wavelengths, something presently not possible with narrow bandgap detectors.

A high D^* for a single pixel is not enough to ensure a high-performance imaging array. Pixel-to-pixel non-uniformities produce a spatial fixed pattern noise (evident in the image of a test uniform scene) which has to be minimized too. The general figure of merit to describe the performance of a large imaging array is the noise equivalent temperature difference (NETD), which includes this spatial noise. NETD is the minimum temperature difference across the target that would produce a signal-to-noise ratio of unity, and is a measure of the minimum resolvable temperature difference in a scene.

IMAGING ARRAYS

The 256x256 pixel QWIP arrays are made as follows. The starting material consists of a $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ MQW stack sandwiched between doped contact layers and capped with a thick GaAs layer, epitaxially grown on a 3-inch diameter GaAs wafer. A 256x256 array of random reflectors is first patterned by lithography and selective dry etching of the GaAs cap layer. The QWIPs are then defined by wet chemical etching of trenches (to isolate each pixel from its neighbors) through the MQW stack into the bottom contact layer. The reflector array is then selectively metallized with Au/Ge and Au for top ohmic contact and reflection. A ring contact is simultaneously made to the common bottom contact layer. The pitch of the FPA is 38 pm; each pixel is 28 μm x 28 μm . 25 such FPAs can be simultaneously fabricated on a 3-inch GaAs wafer.

A matching array of iridium bumps is then evaporated on the QWIP arrays for readout circuit **(ROC) hybridization**. Each **FPA** is diced from the wafer and its top face mated (via an iridium bump-bonding process) to the face of a matching 256x256 pixel ROC array (Amber AE- 166). The back of the **FPA-ROC** hybrid is lapped and etched to remove the entire GaAs substrate, leaving only a ~ 4 μm thick **epitaxial** membrane glued to the ROC. The FPA is illuminated through its back; a bias of -1.5 V is applied to each pixel.

HAND-HELD CAMERA

One hybrid was mounted onto a 0.5 Watt Sterling closed-cycle cooler assembly and installed into an Amber RADIANCE1™ camera-body, to demonstrate a hand-held long wavelength **IR** camera (Fig. 4). The camera has 12-bit data resolution, weighs less than 10 pounds, consumes less than 50 Watts, and features push-button control of all imaging parameters. A 32-bit floating-point digital signal processor combined with multi-tasking software provides the speed and power to execute complex image-processing and analysis functions inside the camera body itself. The camera is fitted with a 100 mm focal length germanium (transparent in the 8-12 μm wavelength range) lens with a 5.5 degree field of view.

The measured mean NEAT of the **QWIP** camera is 40 **mK** (removing the lens assembly improves it to 26 mK) at an operating temperature of 70 K, for a 300 K background. The peak quantum efficiency of the **FPA** is 3%, corresponding to an average of **three** passes of **IR** light through the photosensitive MQW region. The low quantum efficiency is partly due to the **FPA** reflecting 30% of the light striking it, and partly due to its 65% fill factor (the remaining 35% being the dead space between pixels). The **uncorrected photocurrent** non-uniformity (which includes a 1 % non-uniformity from the **ROC** and a 1.4% non-uniformity from the optics) is ~ 6.8%. Two-point (17° and 27° Celsius) correction improves this figure to an impressive 0.05%. A mere 10 of the 65,536 pixels are dead (99.98% operability), demonstrating the high yield of GaAs technology.

Videos were shot with the camera at a frame rate of 60 Hz, with the FPA operating at 70 K. Fig. 5a shows an image of a man's face at 8.5 μm . The tiny dark **square** in each frame of his glasses is an 8.5 μm reflection of the FPA itself, i.e., the QWIP FPA is sensitive enough to see its cold self in a mirror! Acetone fumes (invisible to the human

eye) are clearly seen by the camera (Fig, 5b) since acetone strongly absorbs the 8.8 μm radiation from its surroundings. These images attest to the sensitivity of the QWIP staring array camera.

SUMMARY

Rapid progress has been made in the development of long wavelength QWIPs, since they were first experimentally demonstrated several years ago. A mature GaAs growth and processing technology coupled with dramatic improvements in defectivity now make it possible for QWIPs to be fabricated into large imaging arrays operating at the 70 K temperature attainable with standard single-stage Stirling cycle coolers. These advances have allowed us to demonstrate the world's first 256x256 LWIR hand-held camera. Its sharp, inexpensive, low-noise, large area infrared eye (which can be tailored to see a particular IR wavelength) makes the QWIP hand-held camera the best and the most cost-effective new tool for imaging in the interesting 8-12 μm wavelength range.

ACKNOWLEDGMENTS

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REFERENCES

1. For a detailed technical exposition of the QWIP, see S. D. Gunapala and K. M. S. V. Bandara, Physics of Thin Films, Academic Press, 21, 113 (1995), *and references therein.*

FIGURE CAPTIONS

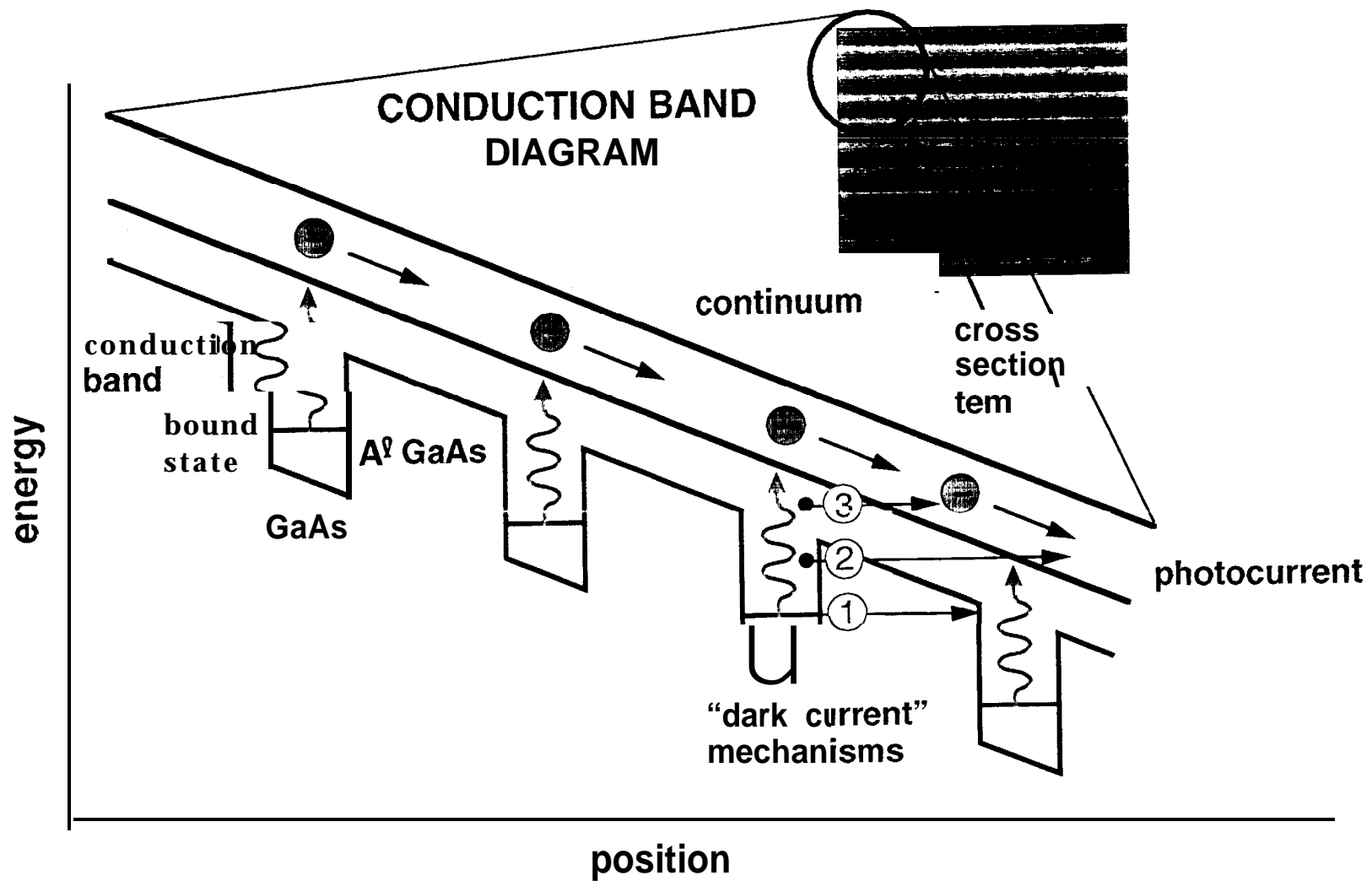
Fig. 1: Infrared photons excite ground state electrons out of a stack of quantum wells in a QWIP producing a **photocurrent** in an applied electric field. Three "**dark-current**" mechanisms are also shown: ground-state sequential tunneling (1); thermally assisted tunneling (2); and thermionic emission (3). Minimizing the dark-current is critical to a successful commercial detector.

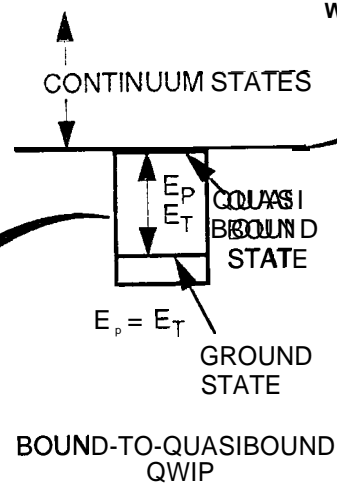
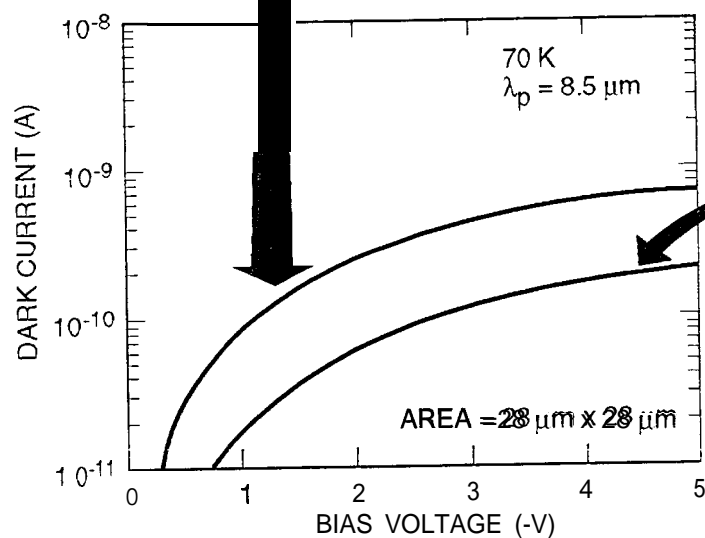
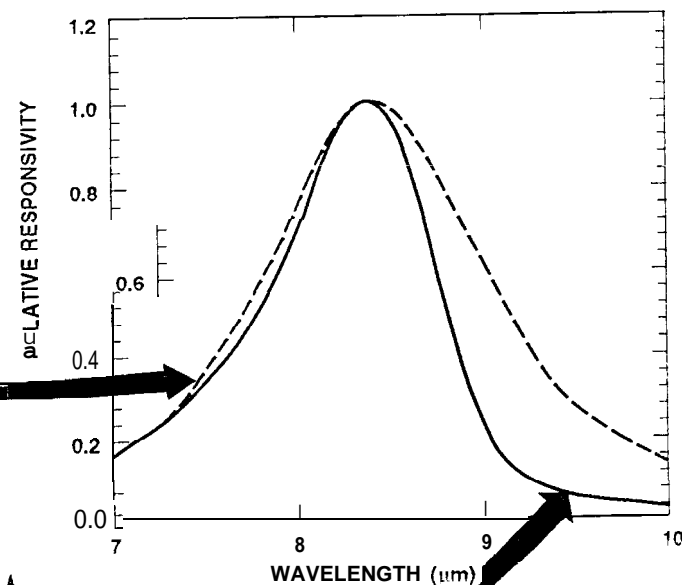
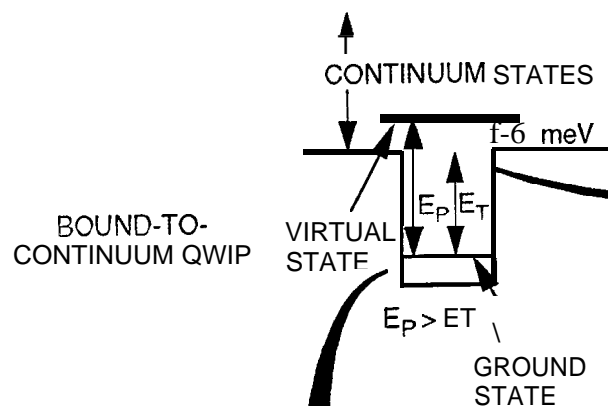
Fig. 2: The dark current decreases significantly when the first excited state is dropped from the continuum (a bound-to-continuum **QWIP**) to the well top (a **bound-to-quasibound QWIP**) without sacrificing the **photocurrent** (inset).

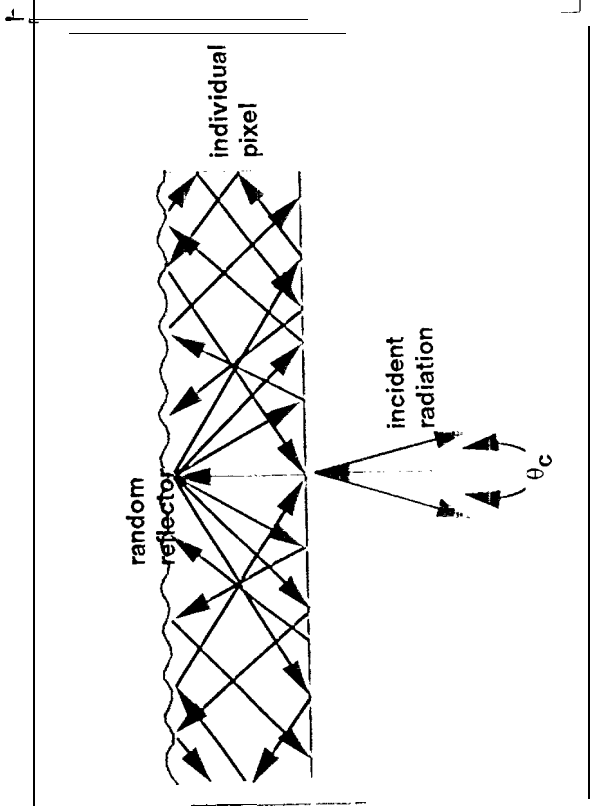
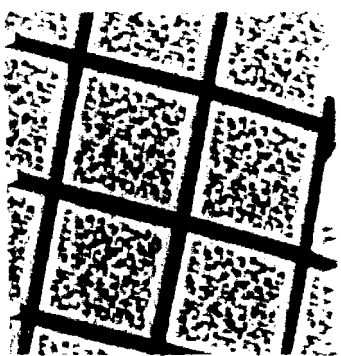
Fig. 3: A random reflector on top of each pixel in a focal plane array (b) bends and traps most of the light that enters the pixel normally through its bottom side, except for a narrow escape cone that is reflected out (a). The bent light is partially absorbed by the electrons in the quantum wells.

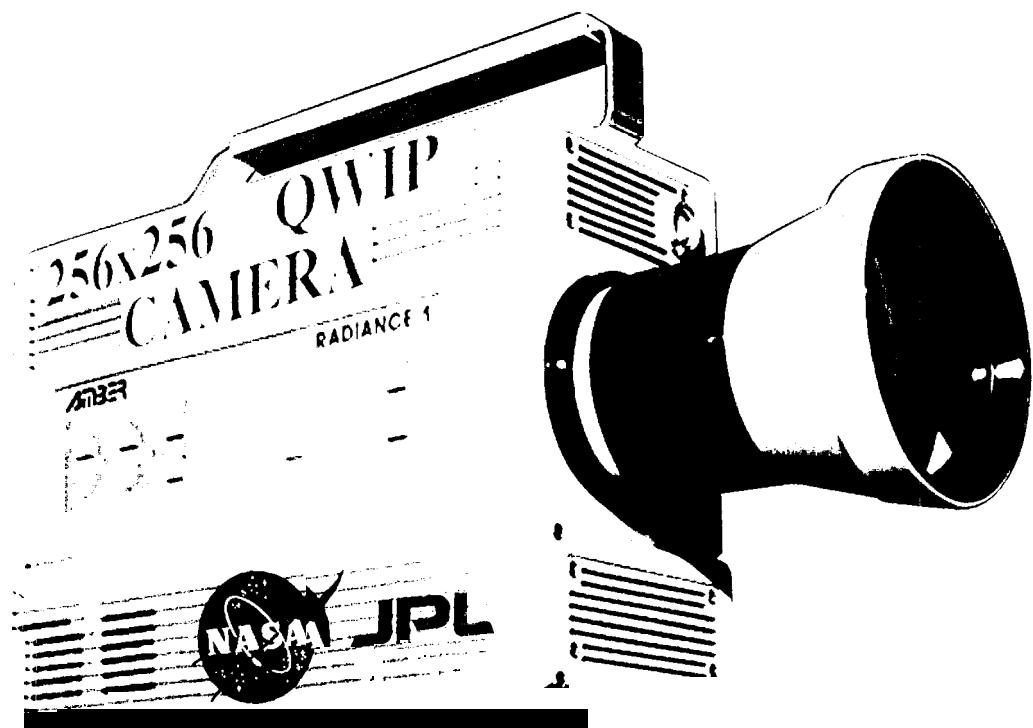
Fig. 4: The world's first hand-held long wavelength infrared camera features a **JPL**-fabricated 256x256 pixel focal plane array of **QWIPs** designed to detect 8.5 μm light mounted in an AMBER Radiance 1 TM camera body.

Fig. 5: An 8.5 μm image of a man's face (a) shot by the QWIP camera shows the QWIP array seeing its own reflection in each frame. of the man's glasses. Normally invisible fumes emanating from an open bottle of acetone are seen by the QWIP camera (b) as acetone fumes absorb 8.8 μm light from the background.









b



a

